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**CORONA INCEPTION VOLTAGE DETERMINATION IN
ELECTROACOUSTIC TRANSDUCER AUTOTRANSFORMERS**

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ABSTRACT

An autotransformer corona inception test circuit has been developed and a prototype has been constructed and demonstrated. Circuit diagrams, component makeup, and component values are presented. Ancillary equipment for the test is identified and recommended, test procedures and precautions are presented, and measured corona inception voltage data and data conclusions, as well as pictorial data are presented for H-core, cup-core, and MPP-core autotransformers.

Key words: Test Equipment, Electrical Measuring, Instrumentation, Non-Destructive Testing

INTRODUCTION

A small but significant percentage of failures in high-power fleet sonar transducers are due to breakdown of electrical insulating or dielectric materials. A physical phenomenon that contributes to these failures is corona (a discharge of electricity caused by ionization of the surrounding medium when the voltage gradient exceeds a certain critical value). The frequency of discharge is above 75 kHz. At high operating voltages corona occurs before dielectric breakdown but will, in time, deteriorate insulating materials and cause dielectric failure.

One of the components in a typical high-power sonar transducer susceptible to corona is the autotransformer (tapped power inductor) that is used to augment tuning, transmit voltage response, and transmit impedance. These transformers usually operate at secondary voltages in the range of 1500 V, but may be as high as 5000 to 6000 V in some instances. A suitable corona test is valuable in determining if a particular transformer design or production transformer has corona at relatively low voltages. Such a situation may be indicative of poor terminal design, voids or air pockets in the coil coatings or potting compounds, and an indication of premature failure in the normal operating environment.

This report presents the development of corona inception voltage (CIV) instrumentation and test procedures that can be applied to all types of autotransformers or coils in various applications.

APPROACH AND OBJECTIVES

The approach to the problem was to develop and use the corona test circuit and make the necessary changes to provide a technically defensible test; that is, defensible in the sense that if a transformer failed to pass the test, the transformer (not the measurement, methodology, or test circuit) would be questionable.

Hardware for the test must be specified and tested to determine if corona can be detected reliably, repeatedly, and economically at the transformer assembly level.

Items needed to accomplish a CIV test, not including ancillary equipment, are: 1) a circuit to resonate with the autotransformer at the approximate center of the operating frequency range; 2) a high-pass filter to attenuate the lower fundamental frequencies, yet allow the higher corona frequencies to be passed for detection; and 3) a properly constructed Faraday shield to provide protection from outside electromagnetic interference which can mask the corona signal.

CORONA INCEPTION VOLTAGE (CIV) TEST CIRCUIT DESCRIPTION

Figure 1 depicts a CIV test circuit, including the ancillary test equipment, that has been developed and validated. In Fig. 1, capacitor C_A , inductor L , and capacitor C_B , are the essential parts of the autotransformer resonant circuit: C_A resonates with the transformer under test, C_B isolates the EMI filter from the rest of the circuit to prevent loading, and L enhances the corona detection by preventing the source from shunting the corona signal. C_A is calculated from the formula for the resonance frequency of an ideal parallel LC circuit which is

$$f_r = \frac{1}{2\pi\sqrt{L_T C_A}} \quad (1)$$

If, in Eq. (1), we define L_T as the inductance of the transformer under test, and f_r as the approximate center of the transformers operating frequency band, then

$$C_A = \frac{1}{4\pi^2 f_r^2 L_T} \quad (2)$$

Figure 2 is a schematic diagram of the EMI filter section of the circuit shown in Fig. 1 and depicts the three-stage ladder, R-C, R-L, high-pass filter which passes the corona signal to an appropriate detector. The circuit component values shown in Fig. 2 were determined by using equations derived from the model of a three-stage, high-pass, L-section filter. The circuit values were verified on a computer program, developed for an L-section filter.

Several different circuits were evaluated to determine the five most optimum values shown in Fig. 3, although all the circuits evaluated were, to some degree, acceptable in that the fundamental frequency would be attenuated while allowing the corona frequency to be passed through for detection. Circuit value set #1 was chosen because at no time did E_{out}/E_{in} exceed 0 dB, and set #1 exhibited a steep cutoff slope. Set #2 also exhibited a steep cutoff slope, but exceeded 0 dB E_{out}/E_{in} . The other circuit values would allow attenuation

of the fundamental frequency, but not to the same degree as set #1. The calculated values (along with actual tests) verified that the circuit would be acceptable for testing several types of transformers with only a change in the value of capacitor C_A , shown in Fig. 1, to resonate the transformer at the center of the operating frequency range.

The quality of the components used in the circuit is very important to eliminate the possibility of corona in any other part of the circuit except the transformer under test. All capacitors are oil-filled polypropylene capacitors and have a dielectric dissipation factor of 0.001 (0.1%) or less.

The inductors for the CIV test circuit were designed and fabricated at NRL-USRD. Inductor L in Fig. 1 consists of 18 turns of #25 polythermaleze insulated copper wire, pi wound on a three-section bobbin. The bobbin assembly is placed into a Ferroxcube #2616-P-3C8 ferrite cup core, and the Q, measured on a RLC bridge, is 68. Inductors L1, L2, and L3 in Fig. 2 consist of 223 turns of #25 polythermaleze insulated copper wire in a Ferroxcube #3622-PA400-3B7 ferrite cup core; and the measured Q is 270.

Figures 4a through 4f are photographs of the test circuit chassis and enclosure. Excluding the ancillary equipment, only the transformer under test is not within the shielded enclosure.

The Faraday shield for the circuit consists of the aluminum chassis bottom, the chassis faceplate, and the copper wire mesh attached by screws to the chassis as shown in Fig. 4a. Shielding the circuit could also be accomplished by enclosure in a metal box or cabinet instead of using a copper mesh. The mesh was used during the development phase to visually determine the existence of any arcing. The circuit components and wiring should be isolated from the the enclosure to minimize any interaction between the return current path of the circuit and the grounded case shield which should not have any current flow. This condition is implied by the single-point ground connection shown in Fig. 1.

The electrical connections between circuit components on the chassis are made with 15 kV dc rated, silicone insulated, 20 AWG stranded copper wire.

CIV TEST PROCEDURES

An oscilloscope with a measurement capability of dc to at least 20 MHz was used. The output connector V1 is connected to the vertical input of the oscilloscope. The oscilloscope was preset to a vertical input sensitivity of 2 V/division and a horizontal sweep time of 20 μ s/division to accommodate the transformers used in the test shown in Tables 1 through 3. The rest of the setup is done as shown in Fig. 1.

The hookup wire from the power amplifier output should be a single twisted pair or coaxial cable rated to accept the maximum anticipated high voltage. All other circuit connections are made with RG-58/U coaxial cable (which will withstand 2 kV) to further shield the circuit from EMI.

In evaluating test procedures, measurements were made with and without transformer shielding and the results indicated that a shield was not necessary for the autotransformers tested. In extremely noisy environments, transformer shielding can easily be accomplished, if necessary; but all ground connections in the circuit should be made at a single point on the chassis.

The following describes the test procedure used in testing the subject autotransformers.

CIV Test Method

1. Adjust the input voltage as read on the VM to the transformer to approximately 5 to 10 V at the approximate resonant frequency [f_r , Eq. (1)] of the autotransformer under test. Then carefully adjust the frequency generator to the frequency that produces the maximum voltage

on the voltmeter, or the maximum amplitude waveform on the oscilloscope.

2. After the frequency is adjusted to resonance, carefully increase the applied voltage until the corona inception "hash" is sporadically observed on the oscilloscope. Corona inception is evidenced by the sporadic high-frequency "hash" type oscillations on the oscilloscope waveform and by an increase in the voltmeter reading. The frequency and the voltage at which corona inception is observed are then recorded.
3. Repeat the first two steps two times to insure repeatability.

Figures 5 and 6 serve to illustrate how the corona "hash" appears on the oscilloscope waveform. Figure 5a shows the oscilloscope waveform for a high power autotransformer under normal drive conditions and Fig. 5b under higher drive conditions that has produced corona. Note that a small amount of the drive frequency is evident in the oscilloscope display; but, as seen in the high drive condition, it is not detrimental to the observance of the corona "hash" in Fig. 5b. Figures 6a and 6b show the same drive conditions just described, respectively, for a higher voltage autotransformer; Fig. 6a shows a clean waveform, and Fig. 6b shows a waveform with high-frequency corona "hash." If desired, corona detection can be augmented if an AM radio receiver is placed near the transformer under test and tuned to 550-560 kHz; sporadic noise (loud static) will be heard from the receiver at the same time that corona "hash" (as illustrated in Figs. 5b and 6b) appears on the oscilloscope wave form.

CIV TEST PRECAUTIONS

The amplifier chosen for the CIV test must be adequate for the intended purpose. For the 4000-V autotransformer test circuit, shown in Fig. 1, the power amplifier selected was an Instruments Inc. Model LDV 2-6, 10 kVA or an equivalent that would supply the current and voltages necessary for the test.

Since a high-impedance output may make the test circuit susceptible to high-frequency noise pickup, one should use the minimum impedance setting on the amplifier compatible with providing the required test voltage across the transformer.

It should be emphasized that corona occurs in the presence of high voltages, and high voltages are required to make the test. The measurements should be made with care and respect for the operating conditions to prevent serious electrical shock to the operator.

CIV TEST DATA

The CIV test circuit and procedures previously described have been used to determine the CIV for several sonar production autotransformers, and for experimental toroidal autotransformers. The autotransformers are fabricated in a variety of ways; i.e., varnish coated but not potted by an encapsulant, potted by an encapsulant, etc. These conditions are noted with the measured data in Tables 1 and 2.

Table 1 provides data from the CIV tests on the 2500-V H-core autotransformers. The serial numbers shown in the table are the actual serial numbers shown on the transformers. The table indicates, in the column headed "Type," certain conditions and materials used in the fabrication of the autotransformer. The table indicates three independent measurements on each autotransformer. Measurements were taken at approximately one-minute intervals.

Table 2 provides corona inception data for several 1400-V ferrite cup core autotransformers. The test circuit shown in Fig. 1 was used to take the data with the following modifications: Capacitor C_A was changed to 3000 pF, and the power amplifier was a McIntosh Model 2500.

CONCLUSIONS

Data from both the cup-core and the H-core autotransformer samples indicate that the cup-core representatives have a smaller standard deviation than representatives from the H-core group. In particular serial #H-1 of the H-core group, with a standard deviation of 324 V, presented an interesting problem. Operator error is the most probable cause of the first excessively high CIV reading for serial #H-1, as the last two readings were much closer to each other (within 7 V). Standard deviations were below 6% of the mean CIV recorded. For this type of measurement, the standard deviations are acceptable. An AM receiver was added to the rest of the ancillary equipment to gather the cup-core and MPP-core data where standard deviations were less than 2% of the mean CIV. The AM receiver has the advantage of providing the operator with an audio reference which complements the visual reference.

ACKNOWLEDGMENTS

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2. Yoshino, H., Sato, K., and Tomago, A., "New Corona-Discharge Detector For Flyback Transformers," National Technical Report Vol. 23 No. 2, Tokyo, Japan, Apr 1977.

Table 1 - Corona Test Data For 2500-V H-Core Autotransformers

SER #	CIV	FREQ (Hz)	CIV	FREQ (Hz)	CIV	FREQ (Hz)	TYPE	CIV	
								MEAN	STD DEV
013	2731	4358	2522	4358	2561	4352	Coated	2604	111
405	2915	4086	2665	4083	2596	4097	Coated	2725	168
H-1	3115	4078	2557	4113	2550	4070	Potted	2741	324
H-2	3007	3962	2825	3999	3110	3973	Potted	2981	144
H-3	2731	4018	2899	4032	2756	4018	Coated	2795	90
A31108	3372	4087	3169	4134	3125	4104	Coated	3222	132
A30433	2549	4086	2778	4105	2882	4096	Coated	2736	170
A22719	3196	4096	2954	4069	3020	4072	Coated	3057	125
A24394	2998	4093	3142	4079	3057	4072	Coated	3066	72
1	3152	4109	3199	4096	3267	4097	Coated	3206	58
2	3428	4106	3137	4117	3203	4116	with corona	3256	153
3	3056	4115	3200	4109	3175	4108	suppressant	3144	77
4	3247	4120	3105	4119	3050	4119	*	3134	102
5	3007	4124	3109	4123	3135	4124		3084	68
6	3108	4120	3013	4121	3135	4118		3085	64
037	2581	4076	2564	4077	2581	4077	Coated	2575	10
041	2522	4070	2479	4069	2526	4069	with	2509	26
054	3003	4071	3100	4068	3044	4069	epoxy	3049	49
058	2570	4068	2605	4069	2500	4068	resin.	2558	53
060	2570	4082	2500	4080	2580	4082		2550	44
061	2700	4079	2816	4078	2703	4079		2760	66

* Hi Temp 221, Hi Temp Resins Inc.

Table 2 - 1400-V Cup-Core And MPP-Core Autotransformer Corona Test Data

SER #	CIV	FREQ (Hz)	CIV	FREQ (Hz)	CIV	FREQ (Hz)	TYPE	CIV	
								MEAN	STD DEV
1	1504	6925	1500	6922	1513	6922	Ferrite	1506	7.0
2	1526	6944	1568	6948	1540	6950	Ferrite	1545	21
3	1500	6942	1517	6945	1522	6942	Ferrite	1513	12
194	1559	6583	1587	6582	1590	6582	Ferrite	1579	17
567	1583	7152	1548	7148	1597	7150	Ferrite	1576	25
617	1559	7088	1556	7087	1560	7086	Ferrite	1558	2.1
MPP 1*	530	6543	600	6531	596	6534	Unpotted	575	39
MPP 2*	1659	6302	1644	6282	1652	6288	Potted	1652	7.5
MPP 3*	545	6533	585	6526	562	6527	Unpotted	564	20
MPP 4*	1655	6235	1650	6234	1659	6235	Potted	1655	4.5

* MPP = Molypermalloy Powder core manufactured by Magnetics Inc.

Potting compound = Eccobond 45 black with 19M catalyst.

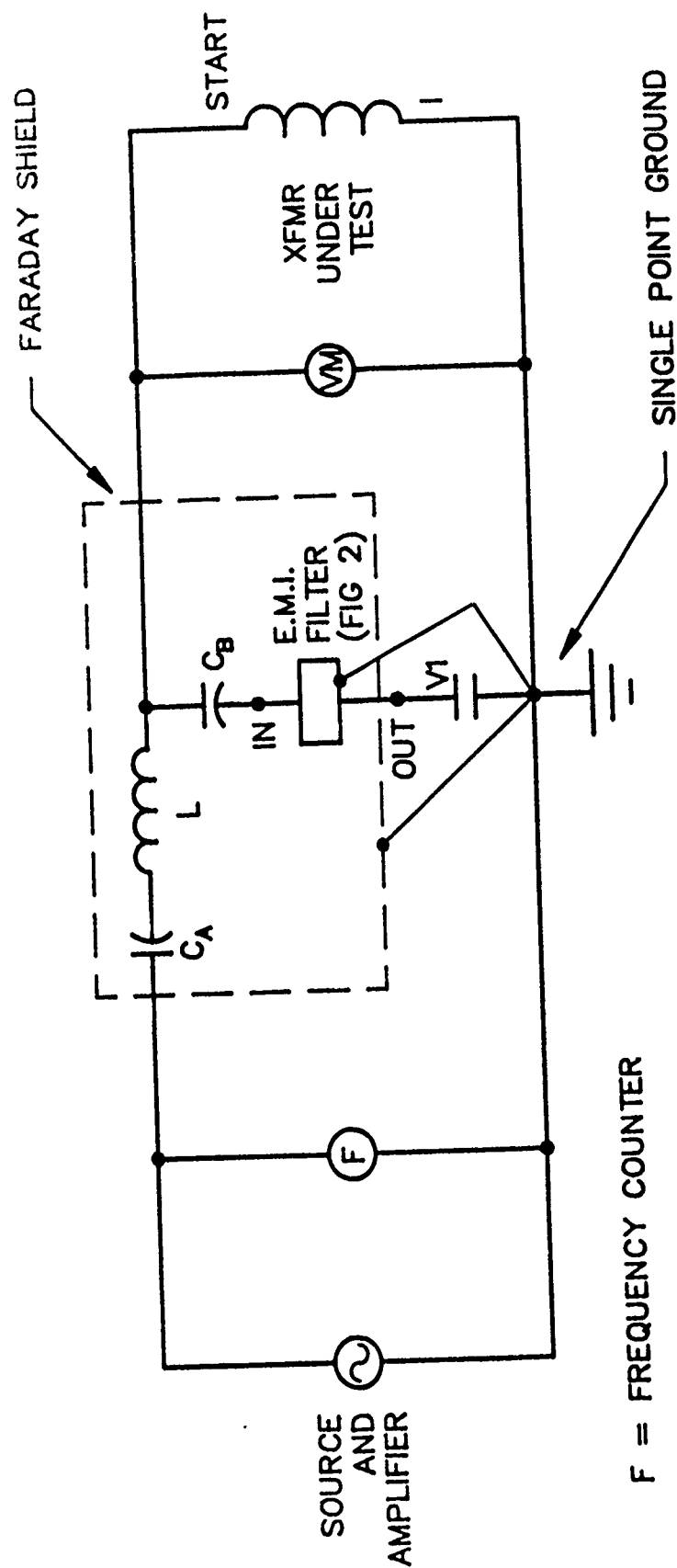
Autotransformer was vacuum potted.

MPP 1 = Unpotted toroid 55251-W4 core.

MPP 2 = Potted toroid 55251-W4 core.

MPP 3 = Unpotted toroid 55248-A2 core.

MPP 4 = Potted toroid 55248-A2 core.



F = FREQUENCY COUNTER

C_A = 5000pF 5000 WDC .1%DF

C_B = 150 pF CAPACITOR 5000 WDC .1%DF

V_1 = INPUT TO OSCILLOSCOPE

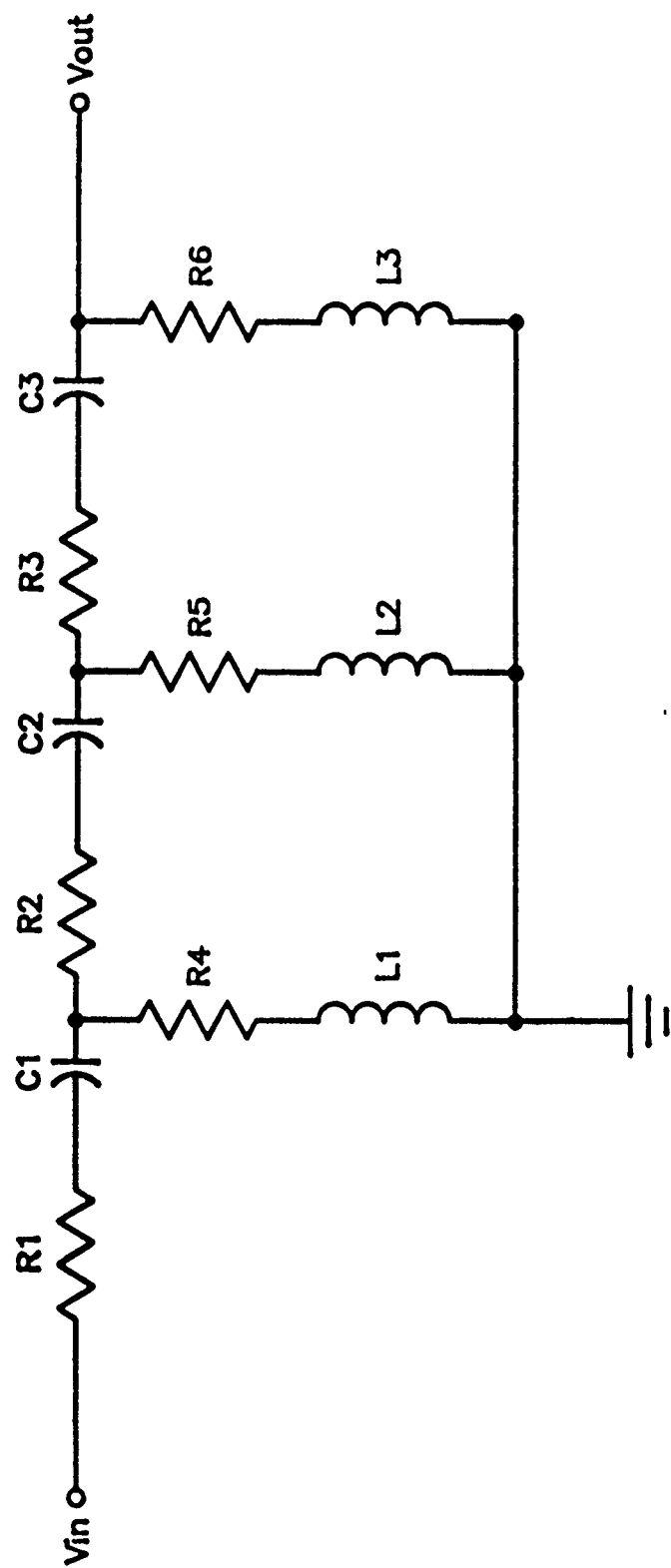
VM = VOLTMETER, FLUKE 8922A TRUE RMS OR EQUIVALENT (USE 100X OR 1000X PROBE).

L = 2.4mH INDUCTOR PIE WOUND LOW CAPACITANCE

SOURCE AND AMPLIFIER = WAVETEK 182A FUNCTION GENERATOR AND INSTRUMENTS INC.,

LDV2-6, 10KVA POWER AMPLIFIER OR EQUIVALENT.

Fig. 1 CIV test circuit.



R1, R2, R3 = 4000 OHMS, 5W

C1 = 0.5 μ F, 3 KVDC

R4 = 400 OHMS, 5W

C2 = 0.2 μ F, 3 KVDC

R5 = 300 OHMS, 5W

C3 = 0.1 μ F, 3 KVDC

R6 = 200 OHMS, 5W

COMPONENT TOLERANCE = $\pm 5\%$

L1, L2, L3 = 0.02H, 0.1 AMP

Fig. 2 EMI filter for CIV test circuit.

E.M.I. HIGH PASS FILTER

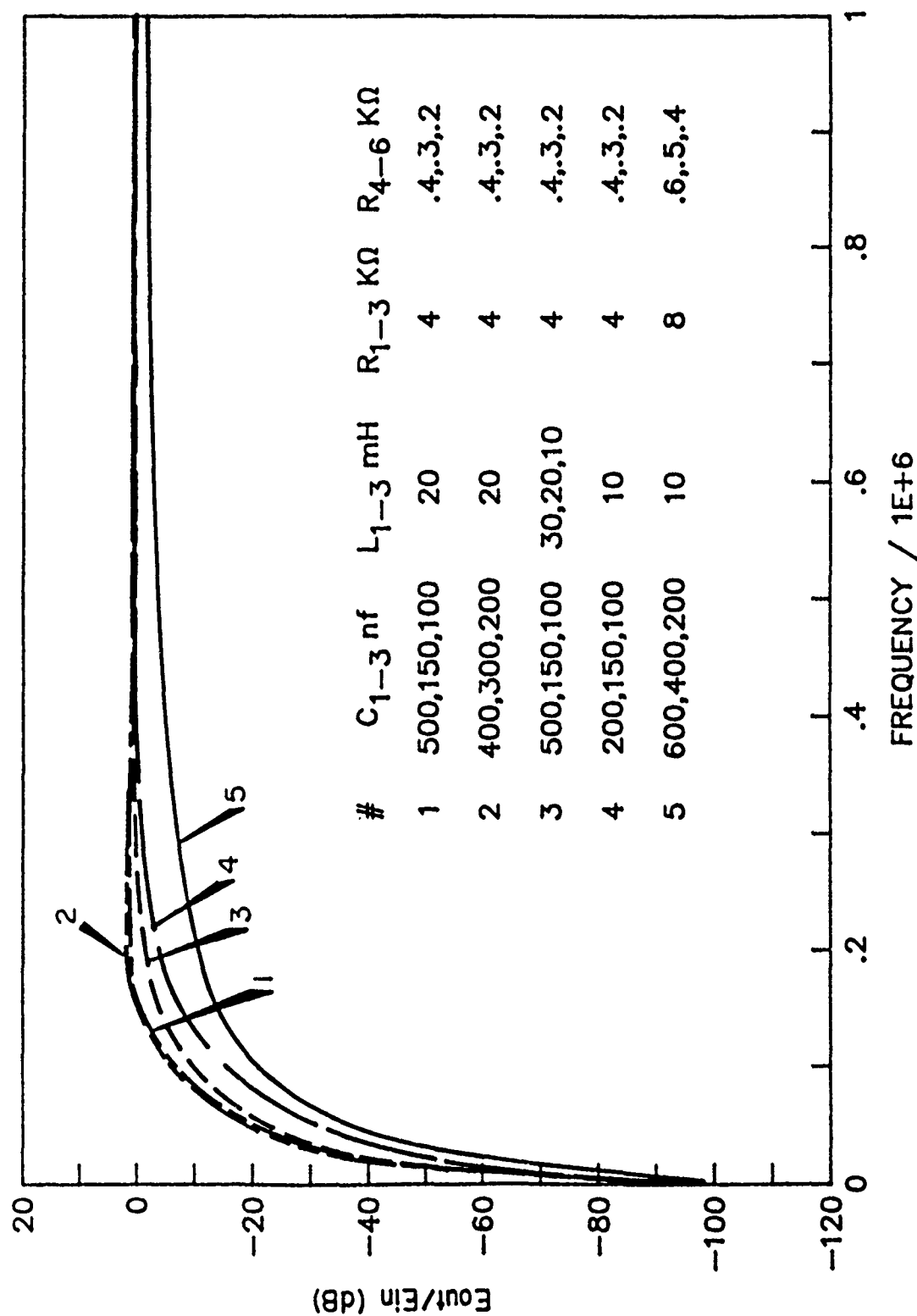


Fig. 3 EMI filter electrical characteristics.

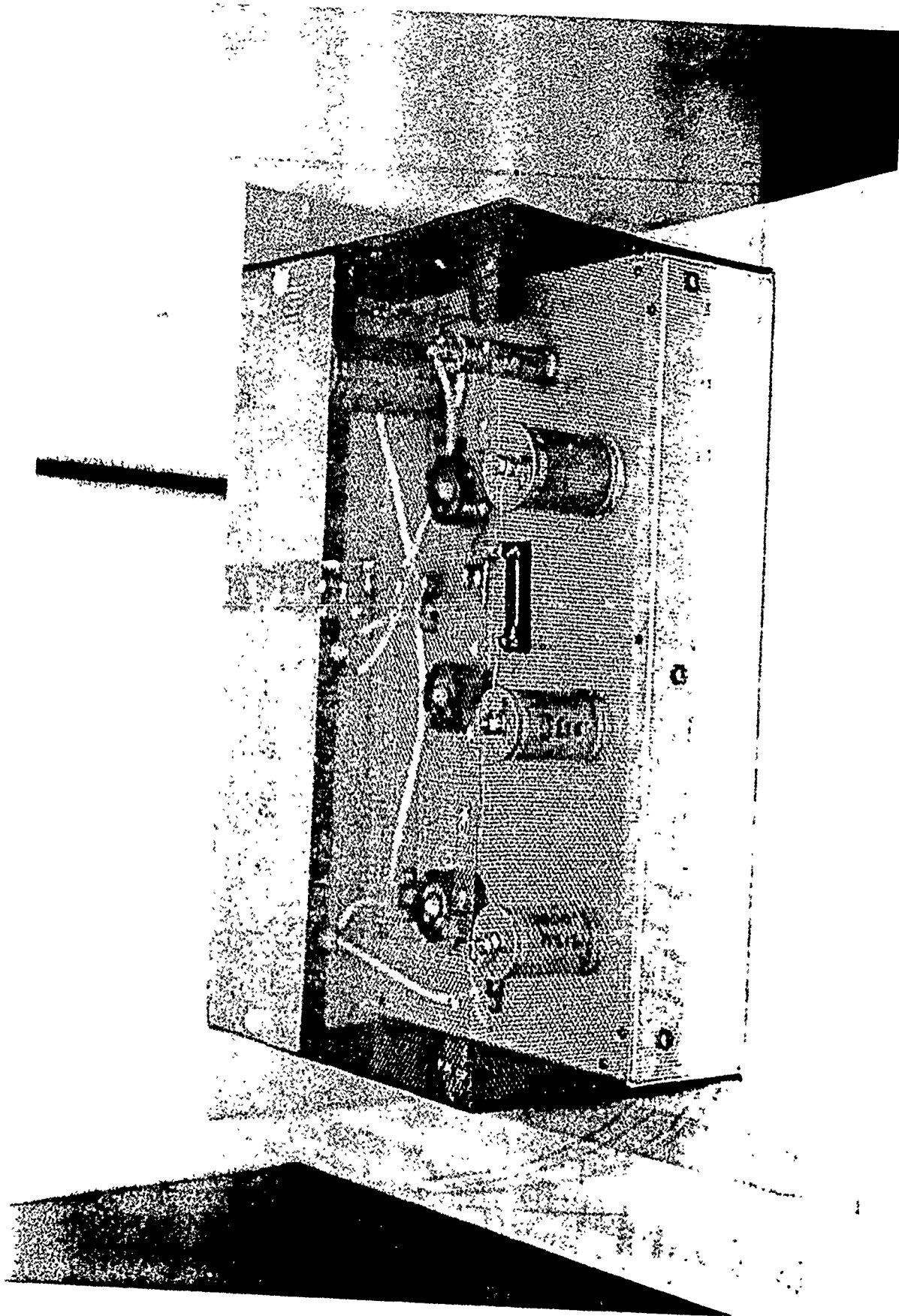


Fig. 4a Rear view with shield mesh installed.

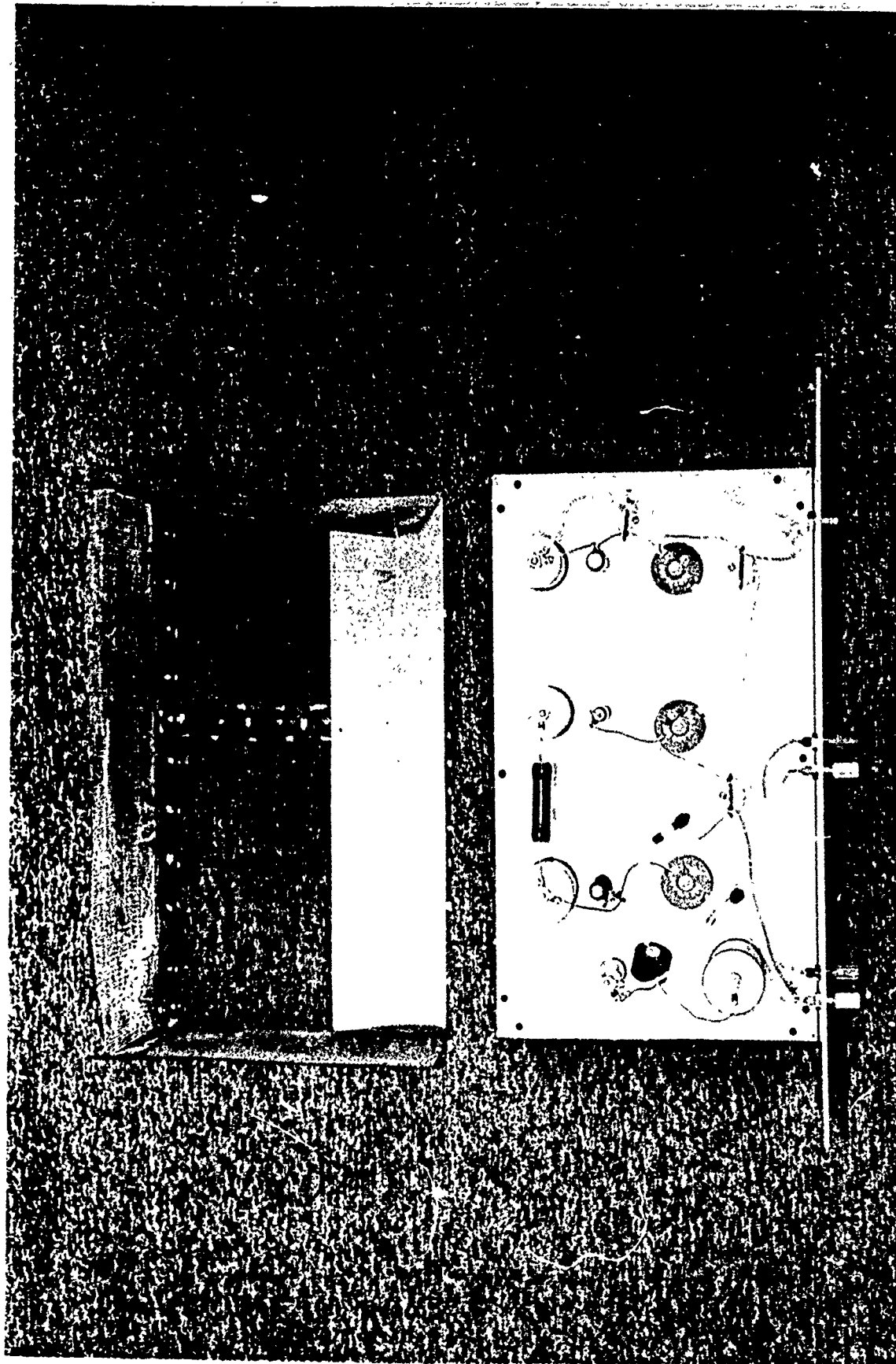


Fig. 4b Top view of component placement with mesh removed.

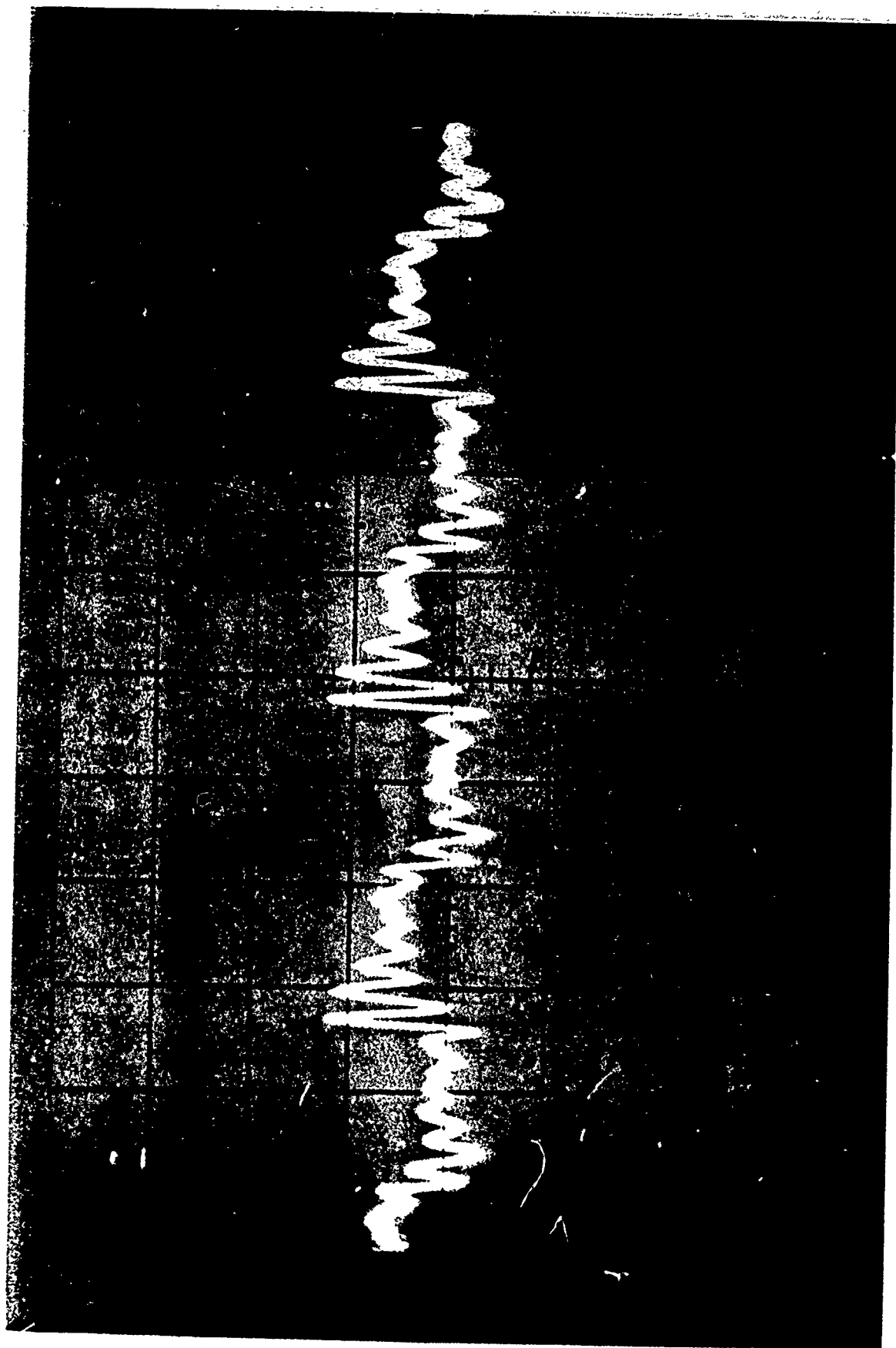


Fig. 5a Output of the CIV test circuit for a ferrite cup-core autotransformer
under normal drive conditions.

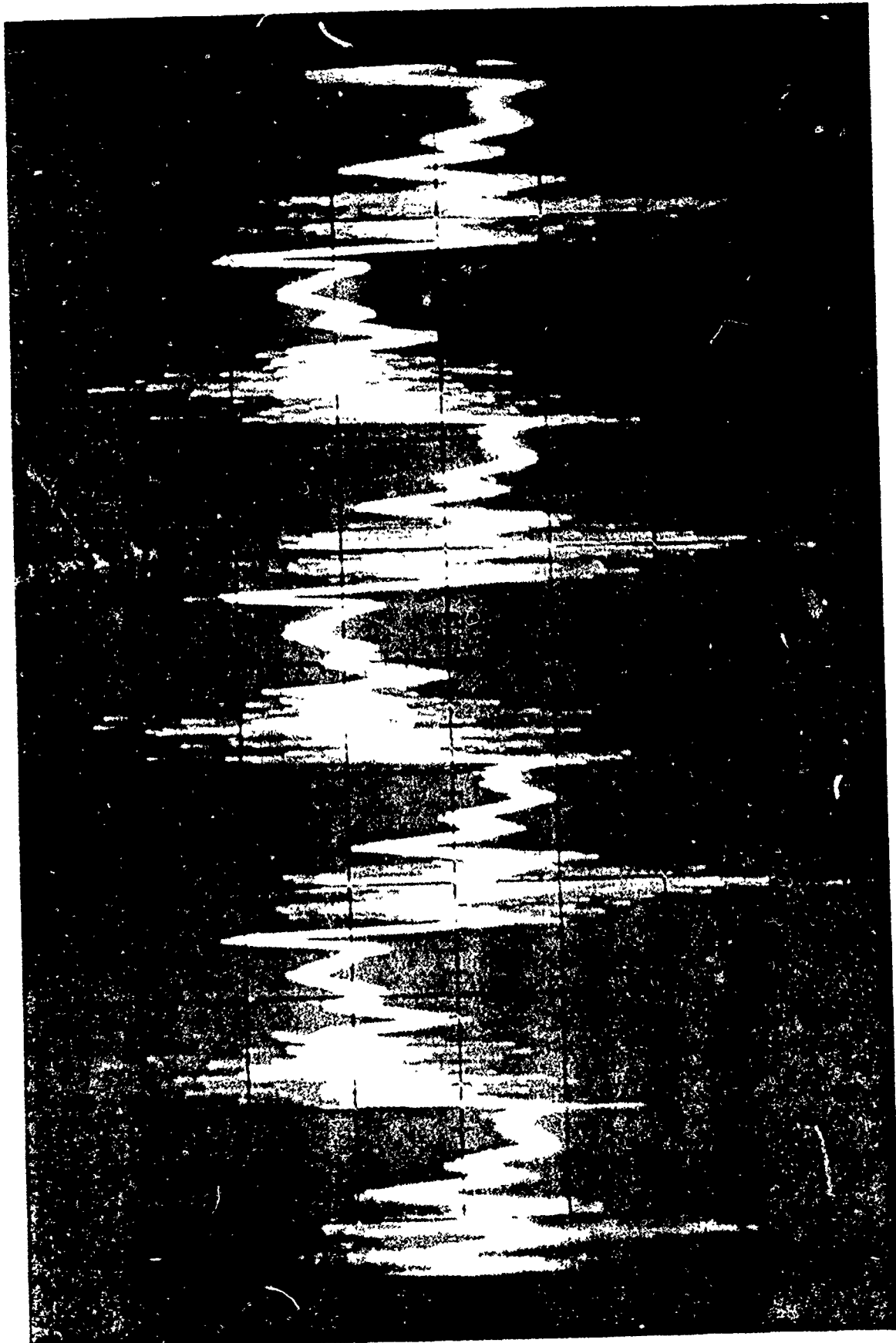


Fig. 5b Output of the CIV test circuit for a ferrite cup-core autotransformer
under high drive conditions with corona "hash."